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ORIGINAL

Thermal conductivity of diethylene glycol based magnesium–aluminum spinel ($MgAl_2O_4$-DG) nanofluids

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Abstract The paper presents the results of measurements of the thermal conductivity of $MgAl_2O_4$-DG nanofluids. The dependence of the thermal conductivity on concentration of nanoparticles in various temperatures from 293.15 to 338.15 K with 15 K step was examined. Experimental data was modeled with existing theoretical models describing the effects of the concentration of particles on the thermal conductivity of the suspension. It was presented that thermal conductivity of $MgAl_2O_4$-DG nanofluids increases proportional to volume concentration of nanoparticles.

1 Introduction

Nanofluids are suspensions of particles of nanometrical sizes in base liquid. Due to the huge potential for the use of these engineering materials [1–3], particularly in the field of heat exchange [4–7] studies on the basic physical properties are conducted by many scientific groups worldwide. Experiments are carried out mainly on rheological and thermal properties, with particular emphasis on thermal conductivity.

Many studies have shown that thermal conductivity of the liquid increases when the nanoparticles are dispersed therein [8–17]. This increase might be particularly interesting both for engineers planning to practical applications of nanofluids as well as for researchers trying to understand the mechanisms responsible for this phenomenon. More specifically, dependence of the thermal conductivity on concentration was examined by Albadr et al. [18] and Xuan et al. [19].

The thermal properties of nanofluids affects not only the nature of the particles in suspension. Anoop et al. [20], and Teng et al. [21] presented, that thermal conductivity increases with decreasing particle size for Al_2O_3 nanofluids, the same relation was presented by Esfe et al. [22] for Fe–water nanofluids. A similar dependence—a decrease in thermal conductivity with increasing size of the nanoparticles—was presented by Wang et al. [23] for Fe_2O_3 particles and Zhou et al. [24].

Another factor which may affect the thermal properties of nanofluids is the shape of the particles in suspension. Jeong et al. [25] conducted a research on ZnO nanofluids which resulted in the show that thermal conductivity of rectangular shape particle suspensions were higher than spheres. Dependence of thermal conductivity on the shape of the nanoparticles in nanofluids was also study by Timofeeva et al. [26].

Thermal conductivity of nanofluids mostly increase with the temperature [10, 27, 28]. But not all nanofluids present that kind of behavior. Mariano et al. [29] have shown that for ethylene glycol-based Co_3O_4 nanofluids thermal conductivity decreases with temperature. Very interesting results of dependence of thermal conductivity on temperature was presented by Li et al. [30] for diathermic oil based SiC nanofluids. They presented that for low volume concentration thermal conductivity decrease with temperature, and for high volume concentration it increase.

In view of the fact that the addition of nanoparticles to liquid relies only on the thermal conductivity increase, it is clear that the type of base liquid used to produce the

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nanofluids is one of the most important factor for the values of thermal conductivity of nanofluids.

Also of interest are the rheological properties of nanofluids. It has been shown that depending on the type of nanoparticles, nanofluids may present Newtonian [17, 27, 29] or non-Newtonian [31–35] nature. In addition, some of nanofluids have interesting electrorheological [36, 37] and magnetorheological [38] properties.

The $MgAl_2O_4$-DG nanofluids present complex rheological properties [39], this materials have non-Newtonian shear-thinning nature. It has been also observed the interesting phenomenon, formation of agglomerates of nanoparticles during rotational viscosity measurements, which resulted in changes in viscosity of nanofluids [40].

2 Materials and methods

2.1 Nanoparticles characterization

The $MgAl_2O_4$ nanopowder which was used in this examinations is commercially available magnesium-aluminum spinel manufactured by Baikowski (Annecy, France), ID LOT: 101488. The average size of the crystallites measured with X-Ray Diffraction was 40 nm, and it was confirmed on scanning electron microscope pictures, which might be found in Ref. [39].

The size distribution of particles is based on measurements of the hydrodynamic diameter in suspension with use of Zetasizer Nano ZS (Malvern Instruments Ltd, Worcestershire, UK). Measurements was conducted on diluted suspensions of particles in diethylene glycol (0.2 g/l), which underwent ultrasonication (VibraCell VCX130, Sonics & Materials, Inc., Newtown, USA) prior measurements. Result of this measurement was presented in Fig. 1. The average hydrodynamic diameter of particles determined on the basis of this method is 215 nm.

To determine the thermal conductivity of $MgAl_2O_4$ nanopowder, its' thermal diffusivity was measured. Thermal diffusivity of the sample was measured at room temperature by the laser flash method utilizing a Laser Flash Apparatus (LFA 427 Netzsch Geraotebau GmbH, Selb, Germany). Then, based on the method presented by Parker et al. [41] thermal conductivity of the material was calculate. Thermal conductivity of $MgAl_2O_4$ nanopowder determined in this measurement is 14.406 W/(m K) at room temperature.

Density of $MgAl_2O_4$ nanopowder was measured with use of a helium pycnometer Ultrapyc 1200e (Quantachrome Instruments, Boynton Beach, USA). Temperature inside measuring chamber was stabilized at 297.15 K by thermostat Grant TC120 (Grant Instruments, Cambridgeshire, GB). The density value was calculate as a average from two series of measurements where each included five unit measurements. Before density measurements nanopowder was dried in temperature of 403.15 K for 2 h. The density of $MgAl_2O_4$ nanopowder is 3.3626 g/(cm^3) at room temperature.

2.2 Sample preparation

Samples were prepared in the various mass concentration (5, 15, 25 wt%) by using an analytical balance WAS 220/X (Radwag, Radom, Poland) with the accuracy of 0.1 mg. In order to break up the agglomerates of nanoparticles mechanical stirring in a mechanical shaker Genius 3 Vortex (IKA, Staufen, Germany) for 30 min, and the ultrasound for a period of 200 min in ultrasoundwave bath Emmi 60 HC (EMAG, Moerfelden-Walldorf, Germany). All samples were prepared at room temperature not exceeding 298.15 K. Volume concentrations of nanofluids were calculated from equation:

$$\varphi_v = \frac{\varphi_m}{\rho_p\left(\frac{\varphi_m}{\rho_p} + \frac{1-\varphi_m}{\rho_0}\right)}, \tag{1}$$

where φ_v and φ_m are volume and mass concentration, ρ_p and ρ_0 stands for density of solid particles and base fluid.

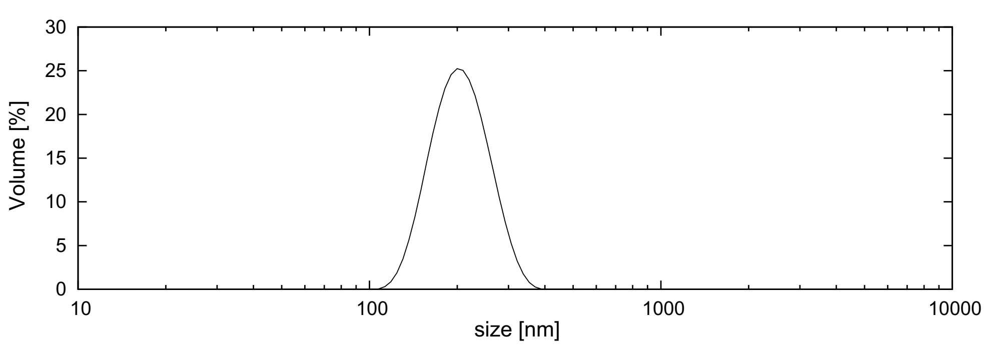

Fig. 1 Hydrodynamic diameter distribution of $MgAl_2O_4$ nanoparticles in diethylene glycol

2.3 Thermal conductivity measurements

To investigate the thermal conductivity of the nanofluids, a KD2 Pro Thermal Properties Analyzer (Decagon Devices Inc., Pullman, Washington, USA) device was used. This equipment is popular, and was previously used by many research groups to study the thermal properties of nanofluids, for example in Ref. [11, 27, 42–45]. The sample was thermostated with the probe in for 30 min in a water bath MLL 547 (AJL Electronic, Cracow, Poland) before measurement. The volume of the examined sample was 30 ml. Time between successive measurements of the thermal conductivity of the sample was 15 min. Uncertainty of measurement did not exceed 2%, and a detailed description of the calibration process has been presented in Ref. [46]. The thermal conductivity of nanofluids were tested immediately after preparation of the sample.

Table 1 Experimental values of the thermal conductivity $MgAl_2O_4$-DG nanofluids

φ_m	φ_v	$k_{nf}\left[\frac{W}{m\cdot K}\right]$ 293.15 K	308.15 K	323.15 K	338.15 K
0.00	0.000	0.2013	0.2060	0.2166	0.2263
0.05	0.017	0.2136	0.2203	0.2310	0.2513
0.15	0.055	0.2400	0.2466	0.2586	0.2707
0.25	0.100	0.2723	0.2803	0.2903	0.3013

3 Results and discussion

Thermal conductivity of $MgAl_2O_4$-DG nanofluids were measured in temperature range from 293.15 to 338.15 K with 15 K step for various volume concentrations between 1.7 and 10%. The results of these measurements are summarized in Table 1. It might be noticed that the thermal conductivity increases with volume concentration of nanoparticles at each measured temperature, as presented in Fig. 2.

In the 19th century, Maxwell [47] presented a theoretical model describing the thermal conductivity of suspensions of spherical particles in the form of:

$$\frac{k_{nf}}{k_0} = \frac{k_p + 2k_0 + 2(k_p - k_0)\varphi_v}{k_p + 2k_0 - (k_p - k_0)\varphi_v}, \tag{2}$$

where k_{nf}, k_p, and k_0 are thermal conductivity of the nanofluid, solid particles, and base fluid respectively. Jeffrey [48] introduced model which considering a suspension of spherical particles:

$$\frac{k_{nf}}{k_0} = 1 + 3\beta\varphi_v + \left(3\beta^2 + \frac{3\beta^3}{4} + \frac{9\beta^3}{16}\frac{\gamma+2}{2\gamma+3} + \frac{3\beta^4}{64} + \cdots\right)\varphi_v^2, \tag{3}$$

where $\beta = \frac{\gamma-1}{\gamma+2}$, and $\gamma = \frac{k_p}{k_0}$.

Turian et al. [49], based on thermal conductivity data on many base fluids presented another model:

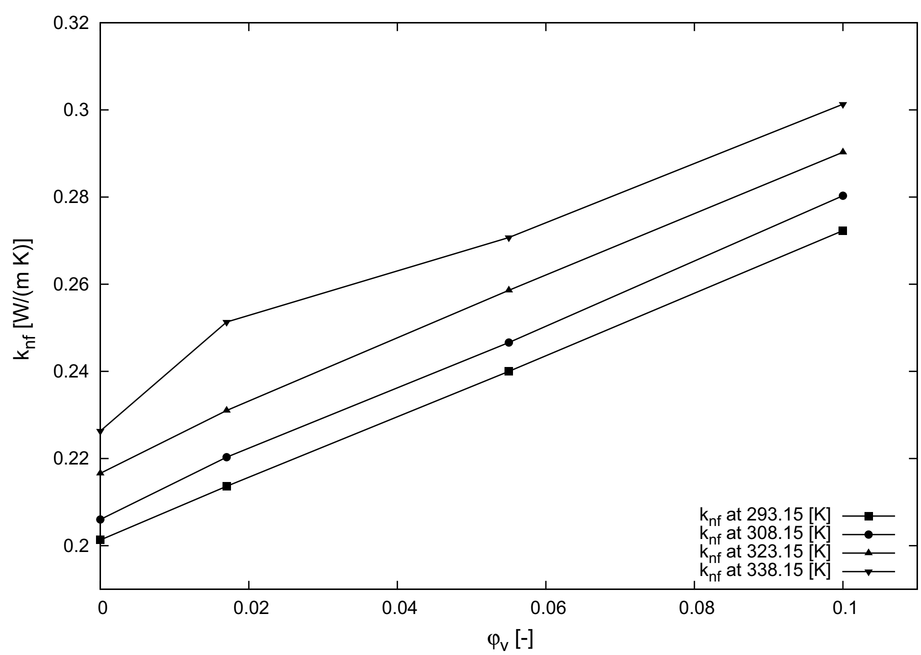

Fig. 2 The dependence of the thermal conductivity of $MgAl_2O_4$-DG nanofluids on volume concentration of nanoparticles for various temperatures

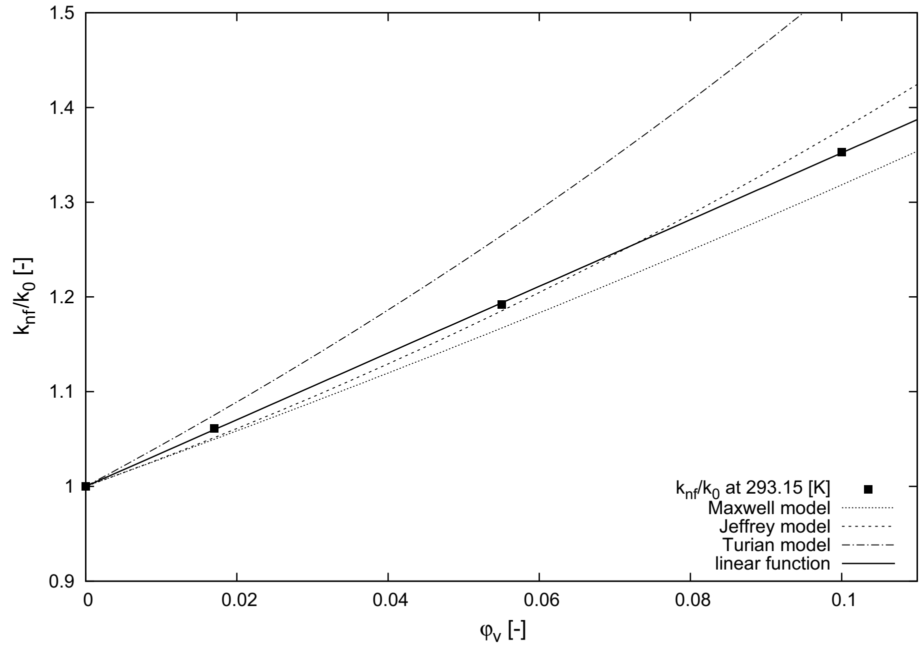

Fig. 3 Thermal conductivity enhancement in $MgAl_2O_4$-DG nanofluid with volume fraction at 293.15 K. *Dots* represent measuring points, *lines* the theoretical model fits

$$\frac{k_{nf}}{k_0} = \frac{k_p^{\varphi_v} k_0^{1-\varphi_v}}{k_0}. \tag{4}$$

Turian et al. assumed that the Maxwell model is right for suspensions, in which $k_p/k_0 \approx 1$, while the model proposed by them had to be right for the suspensions, in which $k_p/k_0 > 4$.

Experimental data for thermal conductivity of $MgAl_2O_4$ -DG nanofluids shows that the k_{nf}/k_0 ratio enhancement is linear with volume concentration of nanoparticles. Using gnuplot software fit a linear function to the received data, was conducted. The function takes form:

$$\frac{k_{nf}}{k_0} = 1 + 3.52029\varphi_v, \tag{5}$$

while asymptotic standard error of parameter was ± 0.01099 (0.3122%).

Figure 3 presents the experimental results, theoretical models fits, and a linear function (5) fit for measurements conducted at 293.15 K.

4 Conclusions

The paper presents results of investigation of the dependence of $MgAl_2O_4$-DG nanofluids thermal conductivity on the volume concentration of nanoparticles at various temperatures. It was presented that the thermal conductivity increase linearly with volume concentration of nanoparticles in nanofluids. It was also found that $MgAl_2O_4$-DG nanofluids presents, repeatedly reported for other types of nanofluids, increase in thermal conductivity with temperature.

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